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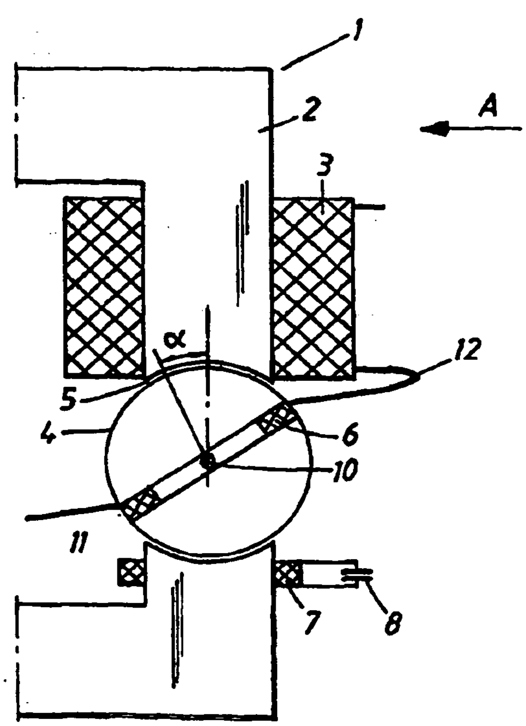
(54) Title: A STEP-FREE INDUCTION CONTROLLED VOLTAGE REGULATOR

(57) Abstract

A step-free induction controlled voltage regulator, primarily for high-voltage regulation, includes a magnetic circuit based upon a magnetizable core (1) having one or more flux paths or legs (2) with at least one winding (3) supplying the output voltage (U). The output winding leg (2) includes a regulation arrangement (4-8) comprising a rotatable rotor means (4) carrying a regulator winding (6) electrically connected in series with the output winding (3). A compensator winding (7) can be arranged around the leg (2) and electrically connected in series with a capacitor means (8). At least one of the regulator winding (6) and the supply winding (3), or a part thereof, is wound by a high-voltage cable comprising at least one conductor surrounded by a first layer having semiconducting properties, a solid insulating layer, and a second layer having semiconducting properties.



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A STEP-FREE INDUCTION CONTROLLED VOLTAGE REGULATOR

Technical Field

The present invention relates generally to step-free induction controlled voltage regulators and more particularly, to such an inductance regulation by an electric transformer or reactor means of the type defined in the preamble of Claim 1. The invention relates also to a regulator winding used by such an induction controlled voltage regulator as defined in Claim 9 and to a method for voltage control in an electrical line or for reactive power control in plants as defined in Claim 18.

Background of the Invention

Conventional induction controlled voltage regulators for lower voltage ranges are arranged by using inductors with coils rotated or shifted in relation to each other as described in the literature, e.g. by I.L. la Cour and K. Faye-Hansen in the book, Die Wechselstromtechnik Bd. 2, "Die Transformatoren", Verlag von Julius Springer, Berlin, Germany, 1936, pages 586 - 598, "Drehtransformator und Schubtransformator". Such an induction control cannot be made for high voltage at reasonable costs. The insulation construction would be a severe design limitation.

Another technique is known from US-A-4 206 434 where the magnetic flux between different legs of an induction controlled voltage regulator is described to be redistributed by a variable DC magnetisation. For this purpose a variable DC-source is needed.

Thus, electric high-voltage control is mostly made by electric transformers involving one or more windings wound on one or more legs of the transformer iron core. The windings involve taps making possible the supply of different voltage levels from the transformer. The present power transformers and distribution transformers as those mentioned above and used in voltage trunk lines involve tap-changers for the voltage regulation. They are subject to mechanical wear and electrophysical erosion due to discharges between contacts. Regulation is only possible in steps. Thus, a stepwise voltage regulation and movable contacts are required for connection with the diff rent taps.

Summary of the invention

The drawbacks of prior art voltage regulation are avoided by the step-free induction controlled voltage regulator according to the present invention. The characteristic features are to be found in that the magnetic circuit of the output winding leg includes a rotatable rotor means carrying a regulator winding, electrically connected in series with said output winding.

An important condition to make it possible for obtaining such a voltage regulation of high voltages, i.e. 36 kV up to 800 kV, is that at least one of the regulator and output windings, or a part thereof, is constructed of a high-voltage cable which include a conductor, a first layer having semiconducting properties, a solid insulating layer, and a second layer having semiconducting properties. Thus, the transformer/reactor will be of so called "dry" type. The use of such a designed high-voltage cable makes it possible to "capture" the electric field inside the cable insulation. This means that it is possible to design induction controlled voltage regulators for high-voltage applications.

An additional advantage is that said layers are arranged to adhere to one another even when the cable is bent. Hereby, good contact is achieved between the layers during the cable's entire life.

To avoid the behaviour as a rotating motor, the rotor means is suitably restricted by a self-locking means only to allow a rotation of one revolution in forward and backward direction. The regulator winding cable connection to the output winding is made through flexible cables, favourably of rubber elastic type.

The higher reluctance generated in the air gaps between the core and the rotor means can be compensated for by a further compensator winding surrounding the magnetic flux. The compensator winding is electrically connected in series with a capacitor as a separate closed circuit.

Such a compensator winding loaded with a capacitor forms a negative reluctance $R_C = -n^2 \omega^2 C$. The number of winding turns n and the regulation of the capacitor capacitance C may be chosen in such a way to correspond to the air gap positive reluctance $R_L = l/A \mu_0$, where

l is the (effective) length of the air gap,

A is the cross section area of the magnetic core, and

μ_0 is the permeability of the air.

Typical valu s of the capacitance C are in th order of from some microfarads to some millifarads for voltages in the order of 1 kV.

By the transformer or reactor construction described above, it is possible to obtain a step-free induction controlled voltage regulation. This is due to the fact that the voltage U_r induced in the regulator winding 6 is determined by the rotation angle α (between the direction of the magnetic flux in the leg 2 and the symmetry surface of the rotor means 4) $U_r \approx n\times\omega\times\Phi\times\cos a$. This results in $U_r = n\times\omega\times\Phi$ for $\alpha = 0$ and in $U_r = n\times(-\omega)\times\Phi$ for $\alpha = \pi$. The zero position ($U_r = 0$) is at $\alpha = \pi/2$.

Different applications lie within the field for the man skilled in the art. Thus, e.g. it is possible to apply the present invention to one-phase induction controlled voltage regulators. Also on-load-tap-changer devices, i.e. a one-phase induction controlled voltage regulator integrated in a transformer, are possible to implement. Furthermore, multi-phase induction controlled voltage regulators can be made with individual phase control as well as with a common phase control.

Brief Description of the Drawings

These and other features and advantages of the present invention will become more apparent from the following detailed description of exemplary embodiments thereof, as illustrated in the accompanying drawings, in which:

Fig. 1 is a principle side view of a part of a transformer core according to the invention,

Fig. 2 is the same part of the transformer core shown in the direction indicated by the arrow A in Fig. 1,

Fig. 3 is a three-phase transformer in which the inventive principle is implemented, and

Fig. 4 is a cross-section view of a high-voltage cable being used in the regulation windings according to the present invention.

Detailed Description of the Invention

The invention will now be described in detail with reference to some preferred embodiments, the principle of which is shown in the drawing figures enclosed. Like reference numbers used in the different drawings refer to similar or

oth r equipm nt having a corresponding function. Figs. 1 and 2 show th part of the voltage regulator only being important to the present invention.

Figs. 1 and 2 show a part of a transformer or reactor core 1 usually in form of a magnetical iron plate package included in the transformer or reactor magnetic circuit. The magnetic circuit would include one or more flux paths 2 (or legs as they will be named in the following description) and in one of which a zone 5 of reduced permeability is arranged in form of a rotatable rotor means 4, which is arranged for obtaining step-free induction controlled voltage regulation. The rotor means 4 is pivoted on an axis 10 in the middle of the zone 5. The rotation of the rotor means 4 is restricted to at least one half revolution, so that the rotation angle α (between the direction of the magnetic flux in the leg 2 and the symmetry surface of the rotor means 4) at least may range between 0 and π. The rotation is restricted in forward and backward direction by means of a worm gear 9 as shown in Fig. 2.

The rotor means 4 is made from a magnetizable material and is provided with a cavity 11 in the periphery surface thereof. A regulator winding 6 is wound in the rotor cavity 11, which regulator winding 6 is in series connection with the output winding 3 of the transformer or reactor. The connection cable 12, Fig. 2, is of flexible type permitting the restricted rotation of the rotor means 4. Thus, the output voltage U is generated over the series circuit of the output winding 3 and the regulator winding 6.

A compensator winding 7 is wound somewhere around the leg 2 including the rotor means 4. The compensator winding 7 is forming a close circuit including a capacitor means 8.

To make it possible to obtain a regulation of high voltages, i.e. in the field of about 36 kV through 800 kV, at least one of the regulator and the output windings 6 and 3, or a part thereof, is wound by using a high-voltage cable 61 of a type shown in Fig. 4 as an example.

The cable used in the present invention is flexible and of a kind which is described in more detail in WO 97/45919 and WO 97/45847. Additional descriptions of the cable concerned can be found in WO 97/45918, WO 97/45930 and WO 97/45931.

Accordingly, th windings, in the arrang m nt according to th invention, are preferably of a type corresponding to cables having solid, extruded insulation, of a type now used for power distribution, such as XLPE-cables or cables with EPR-insulation. Such a cable comprises an inner conductor composed of one or more strand parts, an inner semiconducting layer surrounding the conductor, a solid insulating layer surrounding this and an outer semiconducting layer surrounding the insulating layer. Such cables are flexible, which is an important property in this context since the technology for the arrangement according to the invention is based primarily on winding systems in which the winding is formed from cable which is bent during assembly. The flexibility of an XLPE-cable normally corresponds to a radius of curvature of approximately 20 cm for a cable with a diameter of 30 mm, and a radius of curvature of approximately 65 cm for a cable with a diameter of 80 mm. In the present application the term "flexible" is used to indicate that the winding is flexible down to a radius of curvature in the order of four times the cable diameter, preferably eight to twelve times the cable diameter.

The winding should be constructed to retain its properties even when it is bent and when it is subjected to thermal or mechanical stress during operation. It is vital that the layers retain their adhesion to each other in this context. The material properties of the layers are decisive here, particularly their elasticity and relative coefficients of thermal expansion. In an XLPE-cable, for instance, the insulating layer consists of cross-linked, low-density polyethylene, and the semiconducting layers consist of polyethylene with soot and metal particles mixed in. Changes in volume as a result of temperature fluctuations are completely absorbed as changes in radius in the cable and, thanks to the comparatively slight difference between the coefficients of thermal expansion in the layers in relation to the elasticity of these materials, the radial expansion can take place without the adhesion between the layers being lost.

The material combinations stated above should be considered only as examples. Other combinations fulfilling the conditions specified and also the condition of being semiconducting, i.e. having resistivity within the range of 10^{-1}-10^{6} ohm-cm, e.g. 1-500 ohm-cm, or 10-200 ohm-cm, naturally also fall within the scope of the invention.

The insulating layer may consist, for example, of a solid thermoplastic material such as low-density polyethylene (LDPE), high-density polyethylene (HDPE), polypropylene (PP), polybutylene (PB), polymethyl pentene ("TPX"), cross-linked materials such as cross-linked polyethylene (XLPE), or rubber such as ethylene propylene rubber (EPR) or silicon rubber.

The inner and outer semiconducting layers may be of the same basic material but with particles of conducting material such as soot or metal powder mixed in.

The mechanical properties of these materials, particularly their coefficients of thermal expansion, are affected relatively little by whether soot or metal powder is mixed in or not - at least in the proportions required to achieve the conductivity necessary according to the invention. The insulating layer and the semiconducting layers thus have substantially the same coefficients of thermal expansion.

Ethylene-vinyl-acetate copolymers/nitrile rubber (EVA/NBR), butyl graft polyethylene, ethylene-butyl-acrylate copolymers (EBA) and ethylene-ethyl-acrylate copolymers (EEA) may also constitute suitable polymers for the semiconducting layers.

Even when different types of material are used as base in the various layers, it is desirable for their coefficients of thermal expansion to be substantially the same. This is the case with the combination of the materials listed above.

The materials listed above have relatively good elasticity, with an E-modulus of E<500 MPa, preferably <200 MPa. The elasticity is sufficient for any minor differences between the coefficients of thermal expansion for the materials in the layers to be absorbed in the radial direction of the elasticity so that no cracks appear, or any other damage, and so that the layers are not released from each other. The material in the layers is elastic, and the adhesion between the layers is at least of the same magnitude as in the weakest of the materials.

The conductivity of the two semiconducting layers is sufficient to substantially equalize the potential along each layer. The conductivity of the outer semiconducting layer is sufficiently high to enclose the electrical field within the cable, but sufficiently low not to give rise to significant losses du to currents induced in th longitudinal direction of the layer.

Thus, ach of th two semiconducting layers essentially constitutes on equipotential surface, and these layers will substantially enclose the electrical field between them.

There is, of course, nothing to prevent one or more additional semiconducting layers being arranged in the insulating layer.

Such a high-voltage cable 61 may include one or more electrical conductors 631. The cable embodiment shown in Fig. 4 includes an insulation and the conductor 631 is in direct connection with a first layer 632 having semiconducting properties. The first layer 632 is in turn surrounded by a solid insulating layer 633, which then is surrounded by a second layer 634 having semiconducting properties.

In fig. 4, showing the detail of the invention relating to the cable, the three layers 632, 633, 634 are arranged to adhere to each other even when the cable is bent. The cable shown is flexible, and this property is maintained during the entire life of the cable.

Favourably, the layers 632, 633, 634 are made from the same plastic material or other materials having the same coefficient of expansion. By that, the important advantage is obtained in that deficiencies, cracks, etc. are avoided at thermal movement in the winding. The plastic material of the first and second layers 632, 634 has an electric conductive material added thereto.

Fig. 3 shows the principle for a three-phase transformer constructed according to the present invention. The transformer core 1 comprises three legs 2A, 2B and 2C, each leg carrying a primary winding 15 feeding the transformer with a voltage to be transformed, and an output winding 3 from which the output voltage is obtained. Just as described above with reference to Figs. 1 and 2, each leg 2A, 2B and 2C includes a regulation arrangement 4 - 8. Though not being shown in Fig. 3 for the sake of clarity, each air gap can be compensated by a compensator winding 7 and the capacitor 8 belonging thereto.

The three single-phase regulation arrangements 4 - 8 thus mounted in the three phase legs 2A, 2B, 2C are either manoeuvred jointly, if no voltage asymmetry is expected in the transformer, or individually if each phase should be controlled independ ntly.

Though th present invention has been d scribed above with reference to transformers or reactors it is obvious that it also can be applied to similar apparatuses, e.g. in autotransformers and in booster transformers.

CLAIMS

1. A step-free induction controlled voltage regulator, particularly a transformer or a reactor means, comprising a magnetic circuit involving a magnetizable core (1) having two or more flux paths or legs (2), at least one of which legs being surrounded by an output winding (3), said regulator being **characterized** in that said output winding (3) leg (2) has a regulation arrangement (4 - 8) including a rotatable rotor means (4) carrying a regulator winding (6) connected in series with said output winding (3) and in that at least one of said regulator winding (6) and said output winding (3), or a part of anyone thereof, is wound by a high-voltage cable (61) including a conductor (631), a first layer (632) having semiconducting properties, a solid insulating layer (633) provided around said first layer (632) and a second layer (634) having semiconducting properties provided around the insulating layer (633).

2. A regulator according to claim 1 and further **characterized** by a compensator winding (7) surrounding the output winding (3) leg (2) and electrically connected in series with capacitor means (8).

3. A regulator according to claim 1 or claim 2, and further **characterized** in that the rotation of said rotatable rotor means (4) is restricted to at least half a revolution in forward and backward direction by means of a self-locking means (9).

4. A regulator according to claim 3, and further **characterized** in that said self-locking means (9) is of a worm gear type.

5. A regulator according to any preceding claim, and further **characterized** in that the cable (12) connecting the output winding (3) to the regulator winding (6) is of a rubber elastic type.

6. A regulator according to any preceding claim, and further **characterized** in that said regulator is a multiphase transformer, the output winding (3) leg (2) of

ach phase includ s a regulation arrangement (4 - 8) for independent regulation of each phase.

7. A regulator according to any of the claims 1 - 5, and further **characterized** in that said regulator is a multiphase transformer, the output winding (3) leg (2) of each phase includes a regulation arrangement (4 - 8), the regulation windings (6) of which legs are connected for having a joint regulation.

8. A regulator according to any of the claims 1 - 5, and further **characterized** in that said regulator is an autotransformer or a booster transformer.

9. A regulator according to any preceding claim, **characterized** in that said layers (632, 633, 634) are arranged to adhere to one another even when the cable is bent.

10. A regulator winding (6) for an induction controlled voltage regulator, particularly a transformer or a reactor means comprising at least an output winding (3), according to any of the preceding claims, **characterized** in that at least one of said windings (3, 6), or a part of anyone thereof, comprises at least one current-carrying conductor (631), a first layer (632) having semiconducting properties provided around said conductor (631), a solid insulating layer (633) provided around said first layer (632), and a second layer (634) having semiconducting properties provided around said insulating layer (633).

11. A winding according to claim 10, **characterized** in that the potential of said first layer (632) is substantially equal to the potential and the conductor (631).

12. A winding according to claim 10 or 11, **characterized** in that said second layer (634) is arranged to constitute substantially an equipotential surface surrounding said conductor (631).

13. A winding according to claim 12, **characterized** in that said s cond layer (634) is connected to a specific potential.

14. A winding according to claim 13, **characterized** in that said specific potential is ground potential.

15. A winding according to any of the claims 10 - 14, **characterized** in that at least two of said layers (632 - 634) have substantially equal thermal expansion coefficients.

16. A winding according to any of the claims 10 - 15, further **characterized** in that said current-carrying conductor (631) comprises a number of strands.

17. A winding according to any of the claims 10 - 16, further **characterized** in that each of said three layers (632 - 634) is fixed connected to adjacent layer along substantially the whole connecting surface.

18. A winding according to any of the claims 10 - 17, further **characterized** in that said layers (632, 633, 634) are made from the same plastic material, the plastic material of the first and second layers having an electric conduction material added.

19. A method for voltage control in an electrical line and/or for reactive power control in plants comprising at least a transformer or a reactor having at least one of its windings, or a part of anyone thereof, being of a high-voltage cable type according to any of the preceding claims, where the voltage control is effected by an induction regulation.

20. A method according to claim 19, **characterized** in that said induction regulation is obtained by rotating a rotor means included in the flux path or leg of the transformer/reactor and the permeability of which being influenced by the current supplied through a regulator winding connected in series with the output winding of the transformer/reactor.

21. A method acc rding to claim 20, **characterized** in that the voltage induced in the regulator winding is determined by the rotation angle between the direction of the magnetic flux and the symmetry surface of the rotor means according to the idealised equation $U_r \approx n \times \omega \times \Phi \times \cos \alpha$, where

U_r = induced voltage,

n = number of turns,

$\omega = 2\pi f$, where f = the frequency of the current flowing through the windings,

Φ = magnetic flux, and

α = rotation angle.

Fig. 1

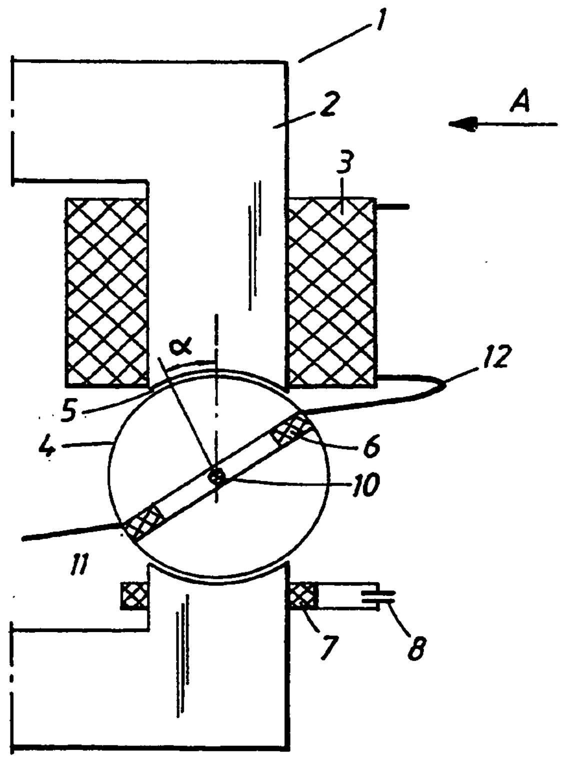


Fig. 2

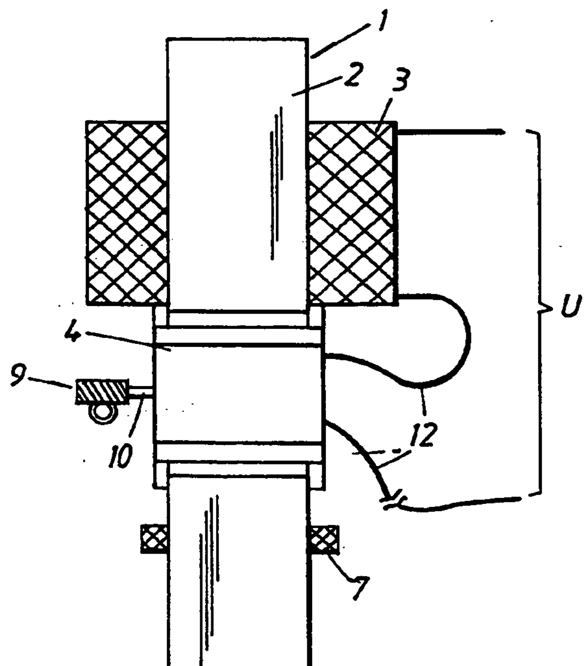


Fig.3

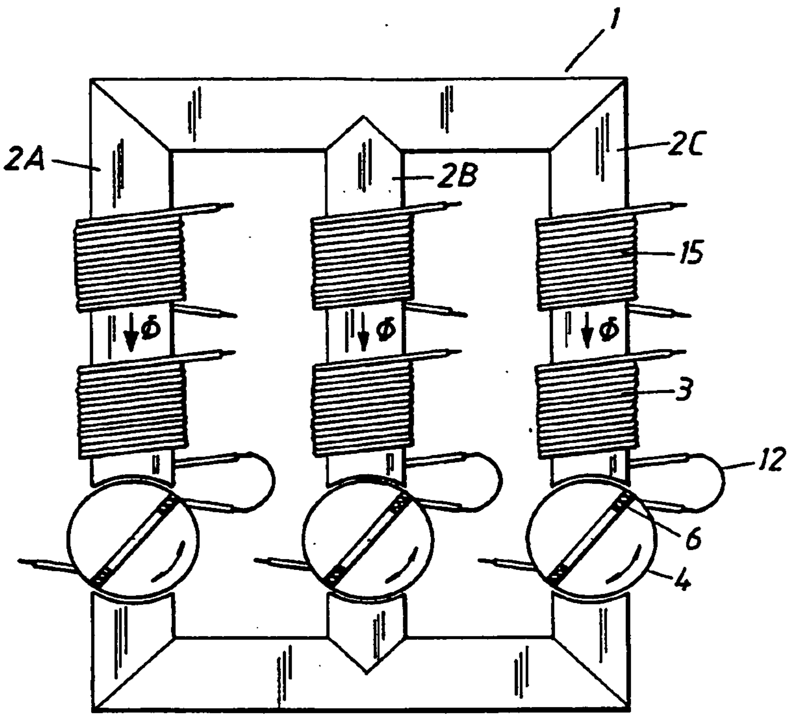
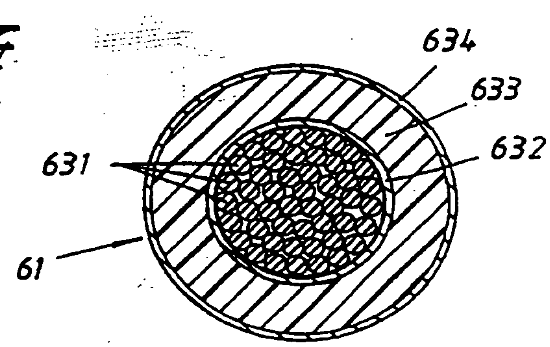


Fig.4



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